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Analysis of LEP Constraints on Supersymmetric Models with a Light Gravitino

John Ellis [1], Jorge L. Lopez[2], and D.V. Nanopoulos[3,4]

[1]Theory Division, CERN, 1211 Geneva 23, Switzerland
[2]Bonner Nuclear Lab, Department of Physics, Rice University
6100 Main Street, Houston, TX 77005, USA
[3]Center for Theoretical Physics, Department of Physics, Texas A&M University
College Station, TX 77843–4242, USA
[4]Astroparticle Physics Group, Houston Advanced Research Center (HARC)
The Mitchell Campus, The Woodlands, TX 77381, USA

Abstract

We propose an analysis of LEP constraints on radiative neutralino decays into a light gravitino, based on the plane of the Higgs mixing parameter μ and the $SU(2)$ gaugino mass M_2. The preliminary LEP 2W constraints in the (μ, M_2) plane are considerably stronger than for supersymmetric models in which the lightest neutralino is stable. A significant portion of the parameter space in which chargino or selectron decay into a final state containing a light gravitino could provide an interpretation of the CDF $e^+e^-\gamma\gamma + \mathrm{E}_{\mathrm{T,miss}}$ event can now excluded by the preliminary LEP 2W data.

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There are three generic phenomenological scenarios for the lightest supersymmetric particle (LSP). Either (i) R parity is violated and the LSP is unstable, or R parity is an exact symmetry and the LSP is stable, in which case it is presumably neutral and at most only weakly interacting [1], and may be either (ii) the lightest neutralino χ, or (iii) some still lighter sparticle such as the gravitino $\widetilde{G}$. Most phenomenological studies have been in the context of the second scenario, in which the χ is the stable LSP [1], though R-violating models (i) have also been studied [2]. R-conserving models (iii), in which the LSP is not the χ, have been around for some time [3, 4], but have only recently attracted considerable attention [5, 6]. This has been revived by the CDF report of a single $e^+e^-\gamma\gamma + \mathrm{E}_{\mathrm{T,miss}}$ event [7], but is an interesting generic possibility in its own right, independent of the CDF report. In our view, this class of models (iii) should be studied in greater depth: in particular, the LEP constraints on this scenario should be explored just as thoroughly as for R-violating models (i), and models (ii) in which the χ is the stable LSP.

Several discussions of the implications of class (iii) models for LEP phenomenology have already appeared [5, 6]. Our purpose here is to propose a general analysis strategy for these models which is adapted from those already used for the other classes of models, and might be suitable for adoption in experimental analyses. Discussions of charginos and neutralinos in models of classes (i) [8] and (ii) usually start from an investigation of the (μ, M_2) plane [9, 10], where μ is the familiar Higgs superpotential mixing parameter, and M_2 is the $SU(2)$ gaugino mass. As in most analyses of class (ii) models, we assume $SU(2) : U(1)$ gaugino universality at the supersymmetric GUT scale, so that $M_1 = (\alpha_1/\alpha_2)M_2$. It is known [11] that this does not affect greatly the (μ, M_2) analysis in class (ii) models, and we do not expect it to be a sensitive assumption here, either. Auxiliary parameters in a (μ, M_2) analysis are the ratio tanβ of Higgs v.e.v.'s, and the masses of the sleptons $\tilde{\ell}$ and $\tilde{\nu}$, which affect the cross sections at LEP for associated production of pairs of neutralinos $\chi_i^0\chi_j^0$ and pair production of the lighter chargino $\chi^+\chi^-$, respectively. The (μ, M_2) plane is well suited for exposing the domain of parameter space in which the CDF event [7] is interpreted as chargino pair production, followed by $\chi^\pm$ decay into a pair of $e+\nu+\gamma+\widetilde{G}$ final states.

It is also usual to analyze LEP constraints on slepton production in class (ii) models using the plane of the parameters $(m_{\tilde{\ell}}, m_\chi)$, which are related simply to underlying supergravity parameters $(m_0, m_{1/2})$ [10]. This plane can also usefully be analyzed in class (iii) models, taking into account the (μ, M_2) analysis proposed above [1]. This type of analysis is useful for comparison with the selectron-pair production interpretation of the CDF event [7].

In this paper, we apply these analysis steps to the preliminary data recently announced by the four LEP collaborations [12], obtained during the recent run of LEP just above the W^+W^- threshold at 161 GeV, which we term LEP 2W. After applying mild experimental cuts [13], no acoplanar $\gamma\gamma+\mathrm{E}_{\mathrm{miss}}$ events were found by the

[1]We note that it is not possible to carry directly over to class (iii) models the results of the slepton searches in class (ii) models, since most of the latter veto events containing photons.

DELPHI, ALEPH and OPAL collaborations, whereas L3 have reported 2 events. On the basis of their absence of events, the DELPHI, ALEPH and OPAL collaborations have quoted preliminary upper limits on the cross section $\sigma_{\gamma\gamma}$ for such events of $\sim 0.5, 0.4$ and 0.4 pb [12], respectively. As a basis for our discussion, we interpret these as a combined LEP 2W upper limit $\sigma_{\gamma\gamma} < 0.2$ pb. Our qualitative conclusions will be insensitive to the precise numerical value of this upper limit [2].

We start by exploring the (μ, M_2) plane for the representative choices $\tan\beta = 2, 8$ shown in Figs. 1, 2. The process which gives the most stringent constraints in this plane is $e^+e^- \to \chi\chi$ (see also [8]), which depends on the selectron mass $m_{\tilde{e}}$ (assumed here to be degenerate: $m_{\tilde{e}_L} = m_{\tilde{e}_R}$), followed by $\chi \to \gamma + \widetilde{G}$ decay. The associated production of χ and χ_2, followed by $\chi_2 \to \chi + \nu + \bar{\nu}$ and $\chi \to \gamma + \tilde{G}$ decays, may also contribute to $\sigma_{\gamma\gamma}$ [6], so it is conservative to retain just the $\chi\chi$ production process. The solid lines correspond to $\sigma_{\gamma\gamma} = 0.2$ pb for the two limiting values $m_{\tilde{e}} = 75, 150$ GeV, the lower value being close to the LEP 2W kinematic limit, and the higher value corresponding to the highest selectron mass consistent with the selectron pair-production interpretation of the CDF event [3]. As an example of the case of non-degenerate masses, for $m_{\tilde{e}_R} = 75\,\mathrm{GeV}$ and $m_{\tilde{e}_L} = 150\,\mathrm{GeV}$ we obtain a line between the two solid lines in Figs. 1, 2. We recall that left- and right-handed selectrons couple differently to neutralinos, depending on the neutralino composition. In the limit $|\mu| \gg M_2$, where the lightest neutralino is asymptotically a pure $\tilde{B}$, its coupling to the $\tilde{e}_R$ is larger than that to the $\tilde{e}_L$, so the common mass we use here would be closer to $m_{\tilde{e}_R}$ in a model with non-degenerate masses.

The domains of parameter space below and between the two arms of the solid lines are excluded by our interpretation of the preliminary LEP 2W data. The dashed lines are the contours where $m_\chi = 80$ GeV, which was the kinematic limit for LEP 2W, which is approached quite closely if $m_{\tilde{e}} = 75$ GeV. The dotted lines are contours of the chargino mass $m_{\chi^\pm} = 80, 100, 150$ GeV. They represent, respectively, the kinematic limit of LEP 2W [4], the lower limit on $m_{\chi^\pm}$ in the chargino interpretation of the CDF event, and an estimate of the upper limit on $m_{\chi^\pm}$ in this interpretation [5]. The dotted region is that in which the chargino interpretation may be valid, with the constraint $m_\chi < 0.6 m_{\chi^\pm}$ also applied [6]. Most models capable of fitting the CDF event in fact have $m_\chi < 0.5 m_{\chi^\pm}$: applying this constraint would bound the dotted region further

[2] Although we have in mind a no-scale supergravity model with a light gravitino [4, 6], the essential features of our approach are also applicable to gauge-mediated models [5], and to models in which the lightest supersymmetric particle is an axino [14], as long as the LSP is very much lighter than the χ.

[3] Note, however, that these choices are not conservative, in the sense that the $\chi\chi$ cross section would be smaller for $m_{\tilde{e}}$ beyond this CDF-motivated range.

[4] We note in passing that LEP 2W searches are probably sensitive to the $e^+e^- \to \chi^+\chi^-$ process for most values of $m_{\chi^\pm}$ up to this limit. In contrast to the conventional stable-neutralino scenario, where experimental sensitivity is lost when $m_{\chi^\pm} > m_{\tilde{\nu}} > m_{\chi^\pm} - 10$ GeV, here there will always be a signature of two energetic photons.

[5] Note, however, that the possibility of models with $m_{\chi^\pm}$ up to 200 GeV has also been considered [5], though the resulting production cross section at the Tevatron may then become rather small.

away from the $\mu = 0$ line, reducing the scope for a model to lie above the $m_{\tilde{e}} = 75$ GeV solid line.

It is immediately apparent from Figs. 1, 2 that the LEP 2W bounds in the class (iii) radiative decay framework discussed here are much stronger than those in the conventional stable-neutralino scenario of class (ii), at least in the region of the (μ, M_2) plane where the lightest neutralino has a predominant gaugino component. In the limit $|\mu| \gg M_2$, where the lightest neutralino is almost a pure $U(1)$ gaugino $\widetilde{B}$, the LEP 2W lower limit on M_2 may be almost a factor two higher in class (iii) models than in class (ii) models. In particular, the direct lower limit $m_{\chi^\pm} > 80$ GeV may be improved to $m_{\chi^\pm} > 150$ GeV for small $m_{\tilde{e}}$.

This observation implies that a significant fraction of the range of $m_{\chi^\pm}$ in which the chargino interpretation of the CDF event is tenable may be excluded by the preliminary LEP 2W data, if $m_{\tilde{e}}$ is not very large. Looking in more detail at Figs. 1, 2, we see that the LEP 2W bounds may be least restrictive for models in which m_χ is close to the upper limit of $0.6 m_{\chi^\pm}$ or for selectron masses that are not too small. It so happens that the specific no-scale supergravity model studied in [6] appears just in this particular region, for $\tan\beta \sim 8$, as indicated by the dot-dashed line in Fig. 2. For reference, in this model the selectron masses when entering (leaving) the chargino region (*i.e.*, for $m_{\chi^\pm} = 100\,(150)$ GeV) are $m_{\tilde{e}_R} = 88\,(115)$ GeV and $m_{\tilde{e}_L} = 133\,(181)$ GeV. Taking these selectron mass variations into account, one may conclude that $m_\chi > 70$ GeV is required, which corresponds to excluding approximately the first half of the portion of the dot-dashed curve that intercepts the dotted region.

We now turn to the analysis of the $(m_\chi, m_{\tilde{e}})$ plane. To simplify this analysis initially, we consider the limit of large $|\mu|$, where χ is asymptotically a pure $\widetilde{B}$ state, and $\tan\beta$ becomes an irrelevant parameter. In this limiting case, we find the contour shown as a solid line in Fig. 3, where $\sigma(e^+e^- \to \chi\chi) = 0.2$ pb, the upper limit on $\sigma_{\gamma\gamma}$ that we infer from the preliminary LEP 2W data. The large-$|\mu|$ asymptotic limits of the solid lines for the values $m_{\tilde{e}} = 75, 150$ GeV in Figs. 1, 2 may be read from this plot.

The region of the $(m_\chi, m_{\tilde{e}})$ plane that is consistent with the kinematics of the selectron interpretation of the CDF event [6] is delineated by the dotted lines in Fig. 3. We see that a significant fraction of this region is excluded by our interpretation of the preliminary LEP 2W data, if one is in the $\widetilde{B}$ limit: $|\mu| \gg M_2$. To assess the significance of the inferred LEP 2W limit for the selectron interpretation away from this limit, we have generated a set of $\tan\beta = 2, 8$ models with $m_\chi < 80$ GeV (so as to be accessible at LEP 2W) and $m_{\chi^\pm} > 125$ GeV (so that the dominant source of events for CDF is selectron-pair production), but no other *a priori* selection of μ or M_2. For each of these models, we have then found the value of $m_{\tilde{e}}$ that yields $\sigma_{\gamma\gamma} = 0.2$ pb. These models are shown as dots in Fig. 3. We see that they cluster relatively close to the $\widetilde{B}$ line. Thus, a non-negligible fraction of the parameter space for the selectron interpretation of the CDF event is also explored by LEP 2W, even away from the $\widetilde{B}$ limit.

The selectron interpretation is therefore significantly constrained by the preliminary LEP 2W data, as we already showed to be the case for the chargino interpretation. Models compatible with both the preliminary LEP 2W data and the selectron interpretation of the CDF event are required to have $m_{\tilde{e}} > 95$ GeV, beyond the reach of future LEP 2 upgrades. In the case of the specific model in Ref. [6], the correlation between the (right-handed) selectron and neutralino masses is indicated by the dot-dashed line, most of which lies within the region consistent with the kinematics of the CDF event in the selectron interpretation. The LEP 2W constraints in this model require $m_\chi > 70\,\mathrm{GeV}$ and $m_{\tilde{e}} > 105$ GeV, bounded from below by a point which lies very close to the pure $\widetilde{B}$ line.

Over the next couple of years, the LEP beam energy will be increased in steps up to about 96 GeV. This will enable the sensitivity in m_χ to be extended to about 95 GeV. As can be seen in Fig. 3, this should be sufficient to explore essentially all the domain of the $(m_\chi, m_{\tilde{e}})$ region compatible with the selectron interpretation of the CDF event, at least in the large-$|\mu|$ limit (and certainly in the model of Ref. [6]). Turning back to Figs. 1, 2, we see that this is not necessarily the case for the chargino interpretation. If $m_{\tilde{e}}$ is large (*i.e.*, $m_{\tilde{e}} \gtrsim 200\,\mathrm{GeV}$), and/or if $m_\chi \to 0.6 m_{\chi^\pm}$, there are regions of parameter space that will not be accessible to LEP 2, even at its maximum energy.

The main purpose of this paper has not been to consider the possible implications of the present preliminary LEP 2W data, or possible future LEP 2 data, for any specific light-gravitino model, whether or not it is motivated by the CDF event. Our objective has rather been to indicate how one may analyze experimental constraints on such models, using an approach adapted from previous analyses of models in which the lightest neutralino is stable. As we have emphasized, the LEP constraints on the unstable-neutralino models may be even stronger than those on stable-neutralino models, because the presence of a pair of energetic photons provides an additional signature that enables, in particular, the process $e^+e^- \to \chi\chi$ – which has the lowest threshold of any supersymmetric process – to be observed. We believe that future analyses by the LEP collaborations will enable a large fraction of the parameter space of such models to be explored.

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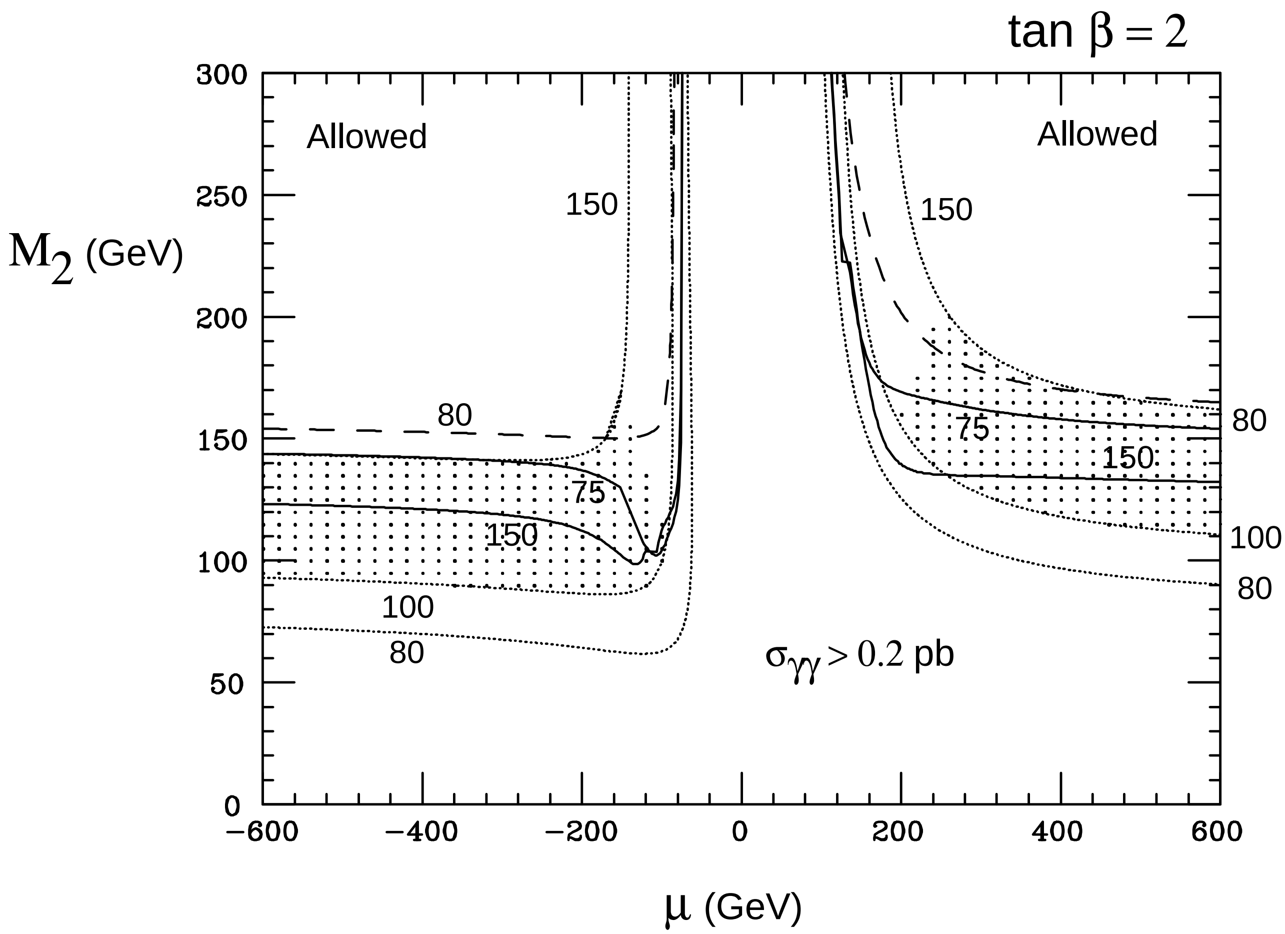

Figure 1: The (μ, M_2) plane for $\tan\beta = 2$, indicating the $\sigma_{\gamma\gamma} = 0.2$ pb contour for $m_{\tilde{e}} = 75, 150$ GeV (solid lines). Domains below and between the two arms of the solid lines are excluded by our interpretation of the LEP 2W data [12]. Also indicated are the contours of $m_\chi = 80$ GeV (dashed lines), and $m_{\chi^\pm} = 80, 100, 150$ GeV (dotted lines). The chargino interpretation of the CDF event [7] requires $m_{\chi^\pm} \approx (100 - 150)$ GeV and $m_\chi < 0.6 m_{\chi^\pm}$ (dotted regions).

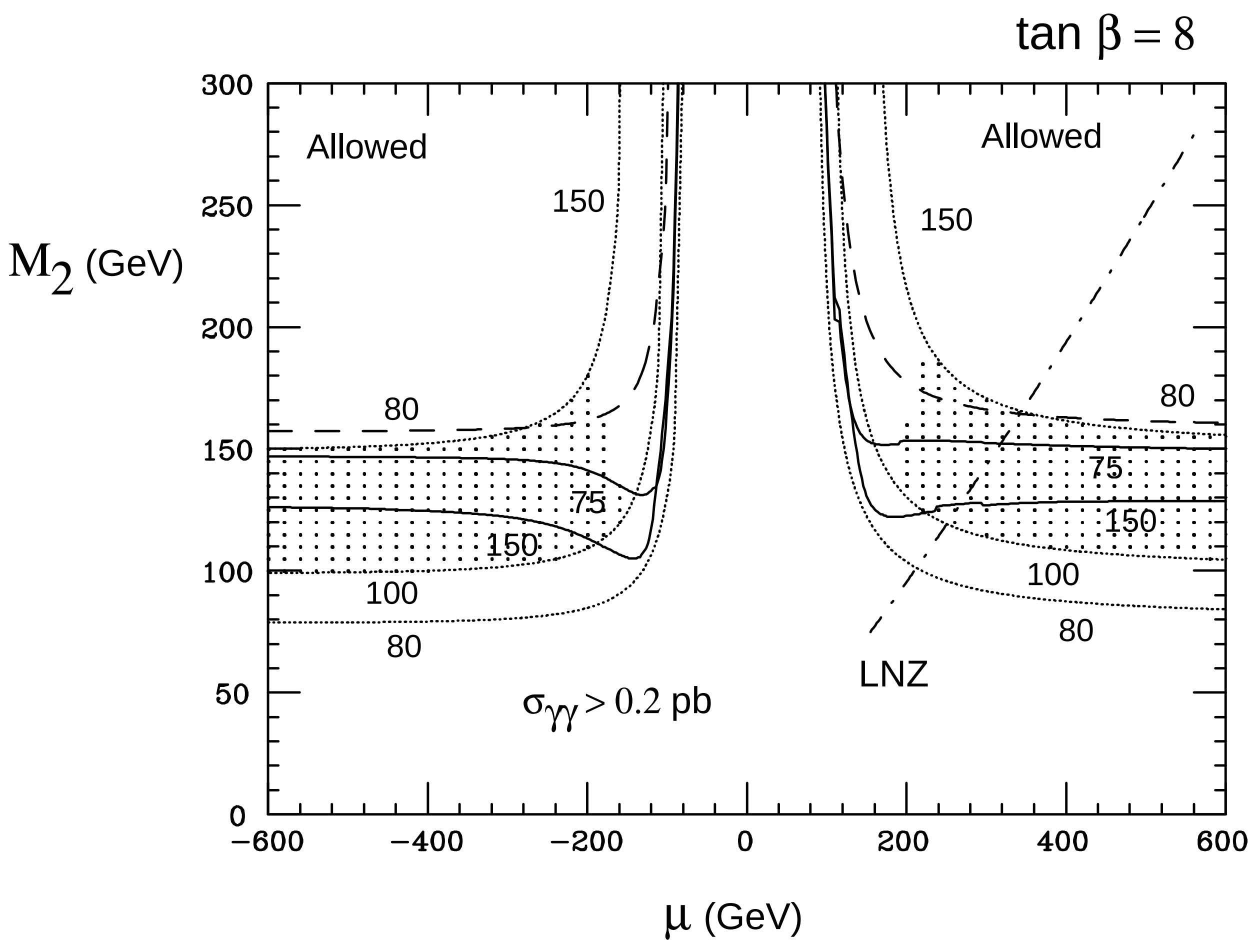

Figure 2: The (μ, M_2) plane for $\tan\beta = 8$, indicating the $\sigma_{\gamma\gamma} = 0.2$ pb contour for $m_{\tilde{e}} = 75, 150$ GeV (solid lines). Domains below and between the two arms of the solid lines are excluded by our interpretation of the LEP 2W data [12]. Also indicated are the contours of $m_\chi = 80$ GeV (dashed lines), and $m_{\chi^\pm} = 80, 100, 150$ GeV (dotted lines). The chargino interpretation of the CDF event [7] requires $m_{\chi^\pm} \approx (100 - 150)$ GeV and $m_\chi < 0.6 m_{\chi^\pm}$ (dotted region). We also indicate the ray singled out in the model of Ref. [6] (dot-dashed line).

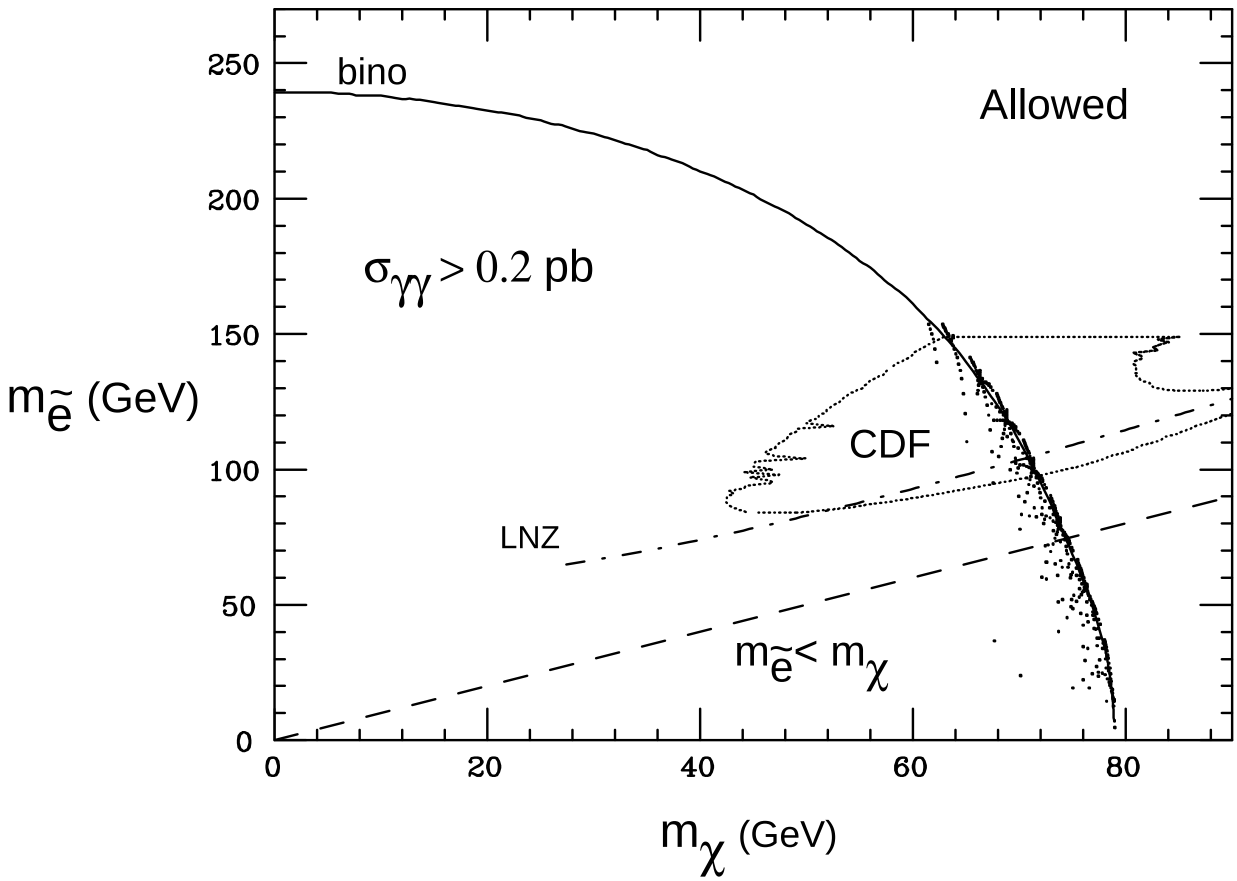

Figure 3: The $(m_\chi, m_{\tilde{e}})$ plane, showing the region where $\sigma(e^+e^- \to \chi\chi) > 0.2$ pb, so that $\sigma_{\gamma\gamma}$ presumably exceeds the limit imposed by the preliminary LEP 2W data [12]. The solid line applies to the limit where χ is a pure $\widetilde{B}$, namely when $|\mu| \gg M_2$. The dots represent models with $m_\chi < 80$ GeV and $m_{\chi^\pm} > 125$ GeV, for which selectron production is likely to be more significant for searches at the Tevatron. The region where the kinematics of the CDF event [7] are compatible with this selectron interpretation is delineated by the dotted lines. We also indicate the line singled out in the model of Ref. [6] (dot-dashed line) and the region where $m_{\tilde{e}} < m_\chi$ (dashed line).